



# Dark energy and dark matter unification via superfluid Chaplygin gas

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## ABSTRACT

A new model describing the dark sector of the universe is established. The model involves Bose–Einstein condensate (BEC) as dark energy (DE) and an excited state above it as dark matter (DM). The condensate is assumed to have a negative pressure and is embodied as an exotic fluid with Chaplygin equation of state. Excitations are described as a quasiparticle gas. It is shown that the model is not in disagreement with the current observations of the cosmic acceleration. The model predicts increase of the effective cosmological constant and a complete disappearance of the matter at the far future.

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## 1. Introduction

The energy content of the Universe is a fundamental issue in cosmology. Observational data are evidence of accelerating flat Friedmann–Robertson–Walker model, constituted of about 1/4 of baryonic and dark matter and about 3/4 of a dark energy component. The DM content was originally inferred from spiral galactic rotation curves and then was supported by gravitational lensing and cosmic microwave background observations.

The essential feature of DE is that its pressure must be negative to reproduce the present accelerated cosmic expansion. The simplest DE model, the cosmological constant, is indeed the vacuum energy with the equation of state  $p = -\rho$ . The models for which  $p < -\rho$  has been denoted phantom energy, and possesses peculiar properties, such as, an infinitely increasing energy density [1], negative temperatures [2], and the violation of the null energy condition. A number of models, such as quintessence [3] and k-essence [4], are based on scalar field theories. These models are parameterized by an equation of state  $p < -\rho/3$ . For a recent review of DE models and references see [5].

An alternative model is that of the Chaplygin gas, also denoted as quartessence, based on a negative pressure fluid, which is inversely proportional to the energy density [6]. The equation of state representing the generalized Chaplygin gas (GCG) is given by  $p_{\text{Ch}} = -A/\rho_{\text{Ch}}^\alpha$  with positive constants  $A$  and  $\alpha$  ( $0 < \alpha \leq 1$ ) [7]. An attractive feature of these models, is that at early times, the energy density behaves as a matter,  $\rho_{\text{Ch}} \propto a^{-3}$ , where  $a$  is the scale

factor, and as a cosmological constant at a later stage,  $\rho_{\text{Ch}} = \text{const}$ . It is also suggested that at an intermediate stage the energy density  $\rho_{\text{Ch}}$  consists of both vacuum and soft matter (matter with the equation of state  $p = \alpha\rho$ ) contributions. This is favorable to use the GCG model for a DE and DM unification [7–9].

Some different approach to the same problem is realized in this work. The feature of the scalar field used in the model [8] is spontaneous symmetry breaking that leads to a nonzero expectation value of the field. In other words, Bose–Einstein condensation of the scalar field into the state with zero momentum takes place. Similar effect holds in the theories of superconductivity and superfluidity. At zero temperature superfluid is in its ground state. If  $T \neq 0$  particle-like excitations arises above the ground state. In this case the system can be divided into a background superfluid condensate and a quasiparticle gas. This separation naturally leads to two-fluid dynamics in which the condensate is said to be a superfluid component and the quasiparticle gas forms a normal component.

The model proposed in this Letter represents the dark sector of the universe as a superfluid where the superfluid condensate is considered as DE and the normal component is interpreted as DM. To provide the accelerated expansion the potential of the scalar field must have specific form and entail a negative pressure of the superfluid background.

We base our analysis on the action

$$S = \int \left( -\frac{R}{16\pi G} + \mathcal{L} \right) \sqrt{-g} d^4x, \quad (1)$$

where Lagrangian  $\mathcal{L}$  associated with a generalized hydrodynamic pressure function depends only on one variable if we consider pure

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